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Thermal Analysis of a Conductively Cooled Spallation Neutron Source (SNS) Fundamental Power Coupler

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Abstract:

A thermal analysis has been performed for a conductively cooled Spallation Neutron Source (SNS) fundamental power coupler with thermal intercepts of 8 K and 50 K. The conduction heat transfer and radiation heat transfer models are developed and discussed. Also included are the results of a parametric study of thermal intercept locations under the operating conditions of the 8 GeV linac currently under design study at Fermilab.

1.0 Introduction

Coaxial power couplers will provide RF power to the Spallation Neutron Source (SNS) linac superconducting cavities. The outer conductors of these power couplers are cooled by a forced flow of 5 K helium. For the 8 GeV linac currently under design study at Fermilab, it is desired to use an electromagnetically similar power coupler that uses a conductively cooled outer conductor. It is expected that conducting heat to the 5 K and 50 K thermal shields will simplify the cryostat design.

Thermal models have been developed to estimate the heat loads to the 2 K cavities, 5 K shield, and 50 K shield. The first model is a conduction heat transfer model. It accounts for conduction from the 300 K end of the power coupler, heat generated due to RF losses, and conduction at 8 K and 50 K to the thermal shields. The second model is a radiation heat transfer model. It accounts for radiation into the 2 K space from the outer conductor, inner conductor, and the 300 K end of the power coupler.

The conduction heat transfer model was used in a parametric study of locating the two thermal intercepts on the power coupler outer conductor. The intercepts can be placed to minimize the 2 K heat load as well as to minimize the theoretical power required by the refrigeration system to remove heat from the multiple temperature levels.

2.0 Conduction heat transfer model

2.1 RF losses

The heat generated due to RF losses along the length of the outer conductor must be calculated in order to determine the outer conductor temperature profile and hence the heat removed by the 8 K and 50 K intercepts.

An estimate of the total heat generated on the outer conductor can be calculated by comparing the operating conditions of SNS and the 8 GeV linac with Equation 1.

$$Q_{8\,\mathrm{GeV}} = Q_{\mathrm{SNS}} \left(\frac{P_{8\,\mathrm{GeV}}}{P_{\mathrm{SNS}}} \right) \left(\frac{t_{\mathrm{pulse},\,8\,\mathrm{GeV}}}{t_{\mathrm{pulse},\,\mathrm{SNS}}} \right) \left(\frac{f_{\mathrm{pulse},\,8\,\mathrm{GeV}}}{f_{\mathrm{pulse},\,\mathrm{SNS}}} \right) \tag{1}$$

The SNS fundamental power coupler outer conductor operates under conditions of 550 kW of power, a 1.3 ms pulse width, and a 60 pps repetition rate [1]. The 8 GeV linac has parameters of 500 kW of power, a 1.3 ms pulse width, and a 10 pps repetition rate [2]. The SNS fundamental power coupler outer conductor RF loss rate of 3 W [1] can therefore be corrected to 0.45 W for the 8 GeV linac.

Because the RF losses are temperature-dependent due to the electrical conductivity, the RF losses are calculated within the conduction heat transfer model using Equations 2-5.

$$Q_{RF\ loss} = I^2_{RMS,\ avg}\ R_{skin} \tag{2}$$

The time-averaged RMS current $I_{RMS,\ avg}$ is a function of peak power P_{peak}, pulse length t_{pulse}, pulse repetition rate f_{pulse}, and coax impedance R_{coax}.

$$I_{RMS,\ avg} = \sqrt{\frac{P_{peak}\ t_{pulse}\ f_{pulse}}{R_{coax}}} \tag{3}$$

The skin resistance R_{skin} of the outer conductor inner surface copper plating (15 μm thick with RRR=10 [1]) is a function of the copper electrical conductivity ρ, length L, and cross-sectional area A of the RF skin as shown by Equation 4. The skin depth δ is calculated by Equation 5, where f is the frequency of the RF power (805 MHz) and μ is the permeability of free space ($4\pi \times 10^{-7}$ H/m).

$$R_{skin} = \frac{\rho\, L}{A} \tag{4}$$

$$\delta = \sqrt{\frac{\rho}{\pi\, f\, \mu}} \tag{5}$$

2.2 Finite difference model

A finite difference model of the outer conductor was written to calculate its temperature profile. The model was written using the Engineering Equation Solver (EES) software package [3]. This is a very powerful software package that can not only solve large sets of simultaneous equations but also allows external library files to be written and used to calculate temperature-dependent material and fluid properties.

The outer conductor was divided into 100 nodes. An energy balance, Equation 6, was written for each of the nodes. Boundary conditions for the set of energy balances were a 300 K warm end and a 2 K cold end as shown in Figure 1. Nodes corresponding to the locations of the 8 K and 50 K intercepts also have specified temperatures of 8 K and 50 K, respectively. The generation term q_{gen} is the RF loss. Using the energy balance, the 2 K heat load and the heat conducted away by the 8 K and 50 K intercepts can be derived.

$$\sum \bar{k}\, A\, \frac{T_{i-1} - T_i}{\Delta L} + q_{gen} = \sum \bar{k}\, A\, \frac{T_i - T_{i+1}}{\Delta L} \tag{6}$$

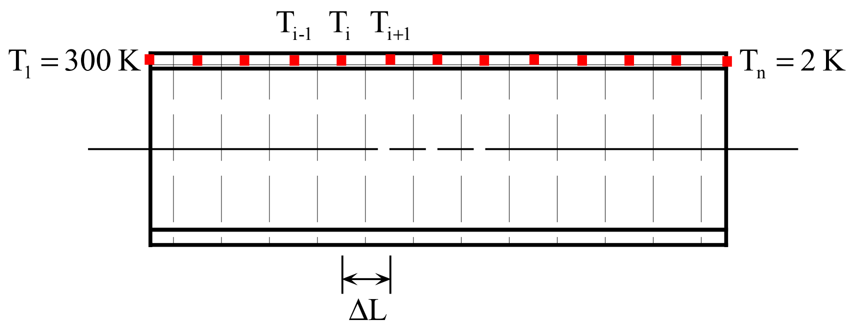

Figure 1 Power coupler outer conductor finite difference model.

The thermal conductivities $\bar{k}$ in Equation 6 are averages of the thermal conductivities at the temperatures of the two nodes involved. The summation indicates that the stainless steel outer conductor and the copper plating are treated as parallel conduction paths with the stainless steel and copper plating at the same temperature within a given node.

The outer conductor RF losses calculated by the finite difference model tend to be lower than the estimated 0.45 W based on operating parameters. The calculated value tends to be lower, about 0.35 W. This could be due to an overall colder outer conductor, resulting in a higher electrical conductivity and therefore lower RF loss of the copper plating.

3.0 Radiation heat transfer model

The dominant heat load to the 2 K cavities is due to radiation heat transfer from the power coupler. An SNS estimate of this heat load is 0.7 W per power coupler [4]. A radiation heat transfer model was constructed to understand the magnitude of this 0.7 W of radiation.

The power coupler was treated as a gray enclosure as illustrated in Figure 2. The enclosure is comprised of four surfaces: the inner conductor (surface 1), the outer conductor (surface 2), the open end looking into the 2 K space (surface 3), and the open end looking into the 300 K space (surface 4).

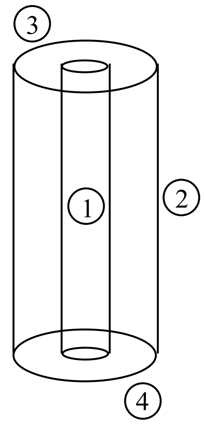

Figure 2 Power coupler gray enclosure model.

Table 1 Calculated view factors for the power coupler gray enclosure.

Fij	i=1	2	3	4
j=1	0	0.397	0.244	0.244
2	0.915	0.5	0.681	0.681
3	0.0425	0.0515	0	0.075
4	0.0425	0.0515	0.075	0

Table 1 shows the calculated view factors F_{ij}. The view factor of the inner conductor to the outer conductor F_{12} was calculated using a tabulated formula for cylinders of finite length [5]. For the view factor of the outer conductor to itself F_{22}, the tabulated formula seemed to have an error so an estimate was made. For cylinders of infinite length and of the radii of the inner and outer conductors (0.6475 in and 1.491 in, respectively), $F_{22} = 0.566$. An estimate of $F_{22} = 0.5$ was made for the power coupler. The remainder of the table was completed using Equations 7 and 8, the reciprocity relation and the summation rule, respectively.

$$A_i F_{ij} = A_j F_{ji} \tag{7}$$

$$\sum_{j=1}^{N} F_{ij} = 1 \tag{8}$$

The radiation heat transfer network of Figure 3 was constructed to model the gray surface enclosure of the power coupler.

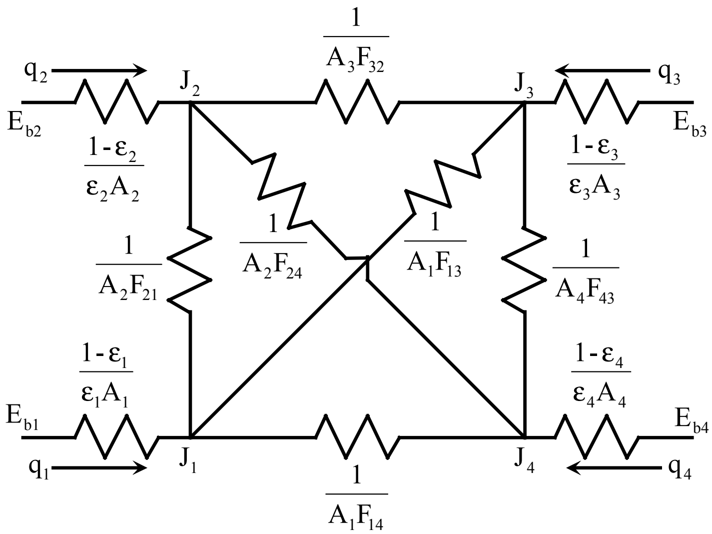

Figure 3 Radiation heat transfer network for the power coupler gray enclosure model.

Surface temperatures are required to calculate the blackbody emissive powers E_{bi}. The inner conductor (surface 1) was taken to be 306 K. The inner conductor RF loss can be estimated with Equation 1, taking the SNS inner conductor 30 W RF loss [1] and correcting for operating conditions. This yields a loss of 4.5 W on the inner conductor for the 8 GeV linac. This low loss in conjunction with the high thermal conductivity of the copper conductor means there is a small temperature gradient along the length of the inner conductor. The 306 K inner conductor temperature also assumes a good thermal path at the room temperature end of the conductor This inner conductor temperature is in good agreement with test data of the SNS power coupler. With 1 gpm of water flow, 600 kW of power, 1.23 ms pulses, and a 60 pps repetition rate, the measured inner conductor tip temperature was 60 C which was a 42 C rise from the measured tip temperature of 18 C under non-powered conditions [6]. Correcting for power and repetition rate, the inner conductor temperature rise in the 8 GeV linac would be expected to be about 6 K. The outer conductor (surface 2) was taken to be at 217 K. This was arrived at by looking at the temperature profile of a stainless steel tube with one end at 300 K and the other end at 2 K. A radiative average temperature was then calculated with Equation 9, which neglects view factor variations along the length. The cold and warm open ends (surfaces 3 and 4, respectively) of the power coupler were taken to be at 2 K and 300 K.

$$A_{s,\,total}\,(\overline{T}^4 - 2^4) = \int (T_i^4 - 2^4)\, dA_{s,\,i} \qquad (9)$$

Solving the resistance network yields radiation heat transfers of about 0.55 W to 2 K. The outer and inner conductors contribute a majority of the radiation heat load, 0.31 W and 0.17 W, respectively. Representative emissivity values are 0.2 for the inner conductor, 0.3 for the outer conductor, 0.7 for the 2 K open end, and 0.7 for the 300 K open end.

The calculated radiation heat transfer compares well with that calculated for the SNS power couplers. Those calculations indicate 0.5-0.6 W depending on emissivities, outer conductor temperature profile, and inner conductor temperature [7].

4.0 Thermal intercept location parametric study

A parametric study was performed to investigate optimization of the thermal intercept locations. There are a couple of ways to look at optimization. One way to optimize the location of the 8 K intercept is to minimize the thermal conduction heat load to 2 K. The 2 K heat load drives the sizing of the refrigerator and auxiliary equipment, such as cold compressors. An effort must be made to keep the 2 K heat load low. A second method of optimization is to look at the Carnot power required to remove the heat loads from the 2 K, 8 K, and 50 K temperature levels. The Carnot power should be minimized. These two optimizations tend to work together anyhow. A large 2 K heat load will result in a large Carnot power.

In addition to looking at the location of the thermal intercepts, the length of the power coupler outer conductor was varied to account for uncertainties in the design of the 8 GeV linac cryostat. The SNS power coupler has an outer conductor length of about 7.7 in. The parametric study was carried out for outer conductor lengths of 7.7 in, 10 in, and 12 in. In all three cases, the outer conductor was taken to be constructed of a 3.062 in outer diameter stainless steel tube with a 0.040 in wall and 15 μm thick RRR=10 copper plating on the inner surface. The 0.040 in wall is the approximate wall thickness of an SNS power coupler outer conductor if the spiral flow passages are removed.

Figure 4 displays the 2 K conduction heat load as a function of 8 K intercept location. The x-axis label of x/L is the 8 K intercept location given as a fraction of the outer conductor length. The 2 K conduction heat load drops off quickly as the 8 K intercept moves away from the 2 K end (x/L = 1), but the 2 K heat load begins to eventually rise as the 8 K intercept moves farther away. This is due to the RF losses in the outer conductor between the 8 K intercept and the 2 K end.

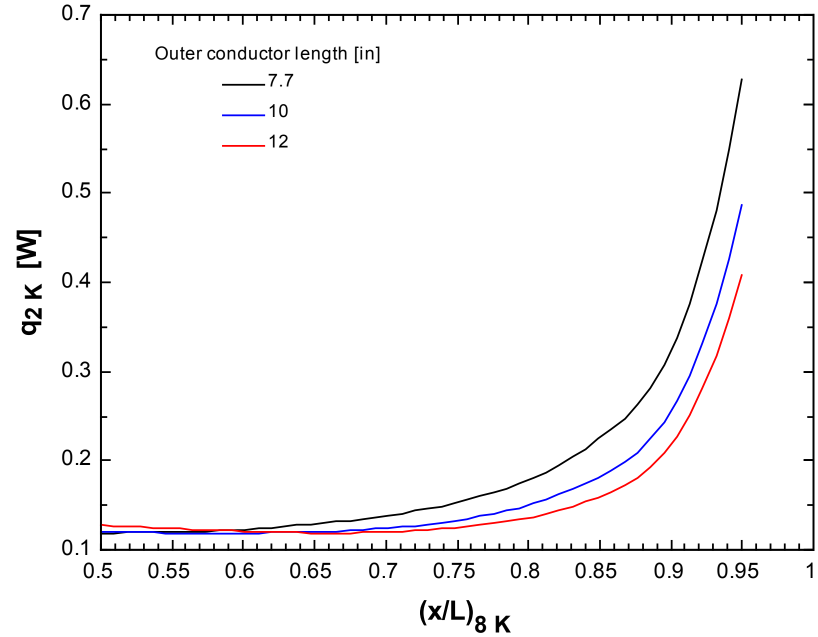

Figure 4 2 K conduction heat load vs. 8 K intercept position.

Figures 5-7 show the heat loads to the 8 K and 50 K intercepts as functions of their positions along outer conductors of length 7.7 in, 10 in, and 12 in, respectively. These heat loads would be useful in designing a refrigerator cycle, but they alone do not yield much information about optimum placement of the thermal intercepts.

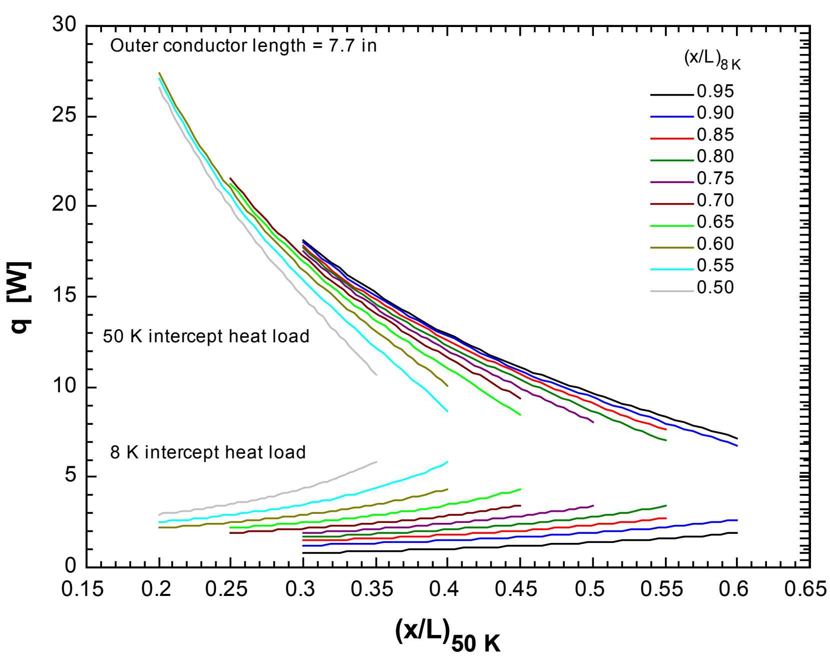

Figure 5 8 K and 50 K intercept heat loads vs. 8 K and 50 K intercept positions for a 7.7 in long outer conductor.

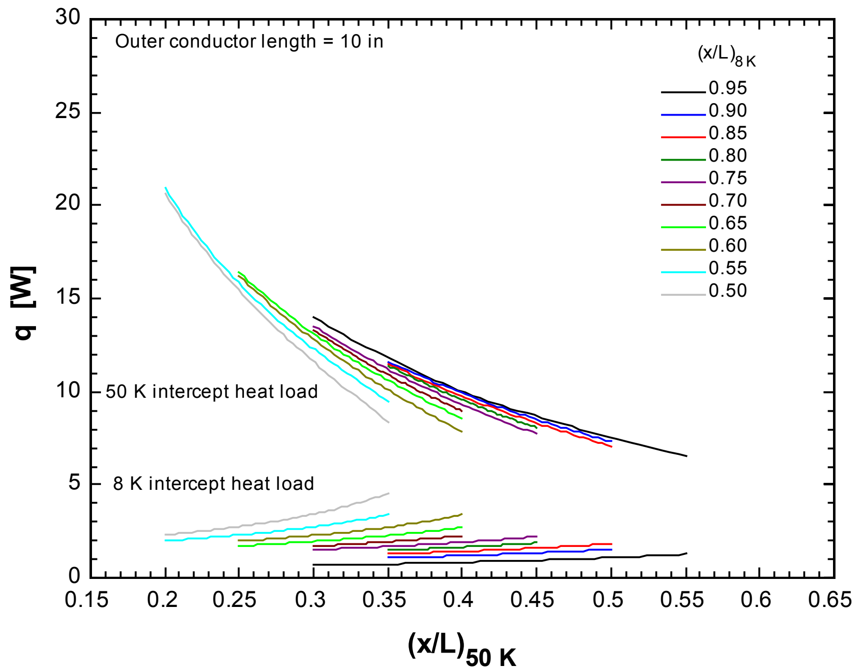

Figure 6 8 K and 50 K intercept heat loads vs. 8 K and 50 K intercept positions for a 10 in long outer conductor.

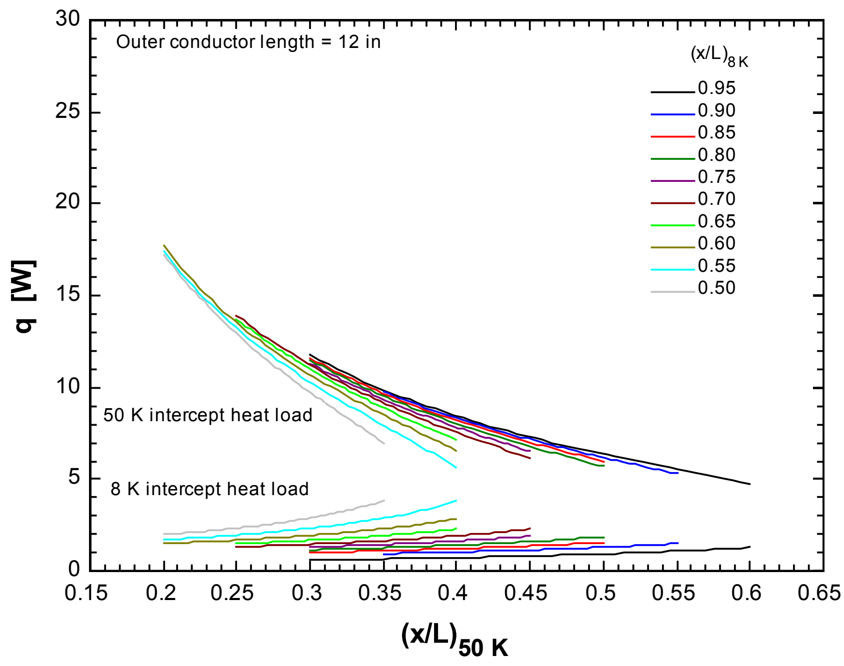

Figure 7 8 K and 50 K intercept heat loads vs. 8 K and 50 K intercept positions for a 12 in long outer conductor.

Figures 8-10 show the minimum theoretical input power (i.e., the Carnot power) as calculated by Equation 10 that would be required by a refrigeration system to remove the heat loads from 2 K, 8 K, and 50 K. In Equation 10, $T_{c,i}$ is a temperature level (2 K, 8 K, or 50 K) and $q_{c,i}$ is the heat load to that temperature level.

$$\dot{W}_{Carnot} = \sum \left(\frac{300 - T_{c,i}}{T_{c,i}} \right) q_{c,i} \tag{10}$$

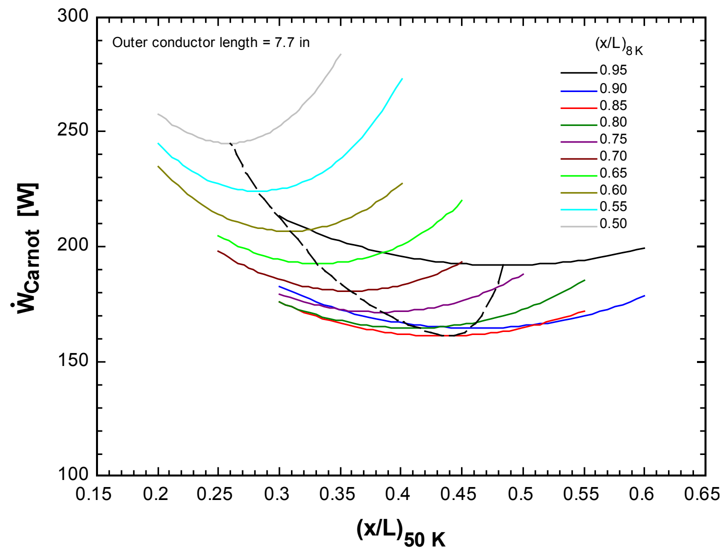

Figure 8 Carnot power vs. 8 K and 50 K intercept positions on a 7.7 in long outer conductor.

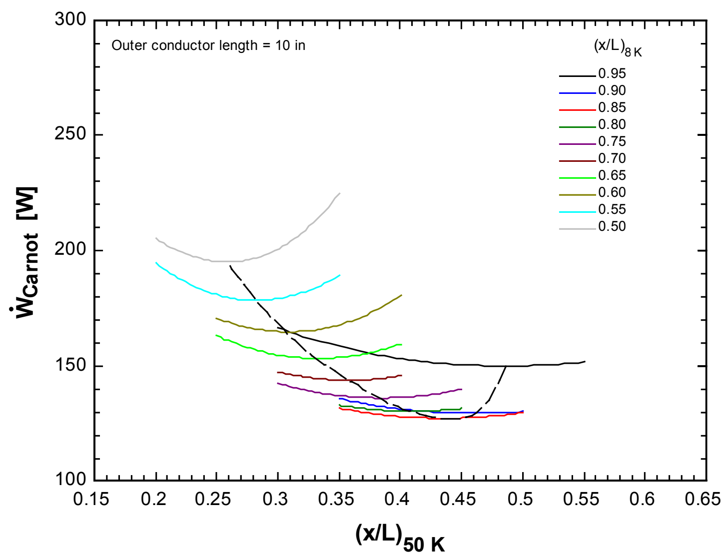

Figure 9 Carnot power vs. 8 K and 50 K intercept positions on a 10 in long outer conductor.

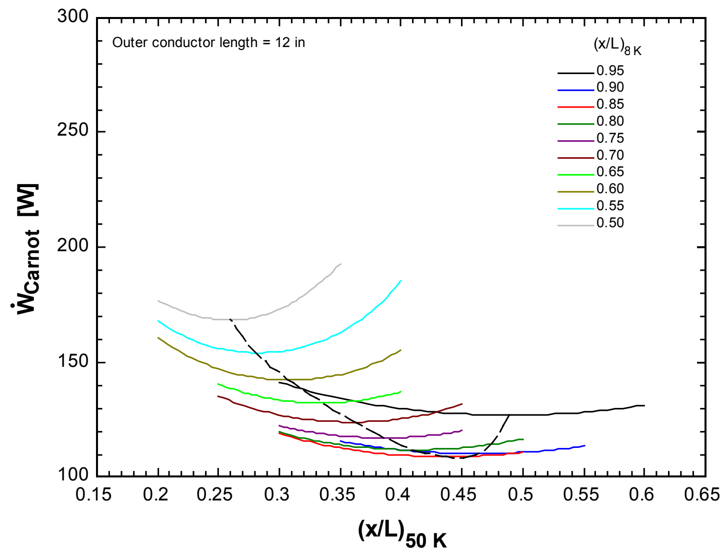

Figure 10 Carnot power vs. 8 K and 50 K intercept positions on a 12 in long outer conductor.

It can be seen that for a given placement of the 8 K intercept, there is an optimum location for the 50 K intercept that minimizes the Carnot power of the refrigeration cycle.

There is also an optimum placement for both the 8 K intercept and the 50 K intercept. The dashed line in each plot of Figures 8-10 is the locus of optimum 50 K intercept locations. The minimum of this dashed line gives the optimum location of both the 8 K and 50 K intercepts. The optimum intercept locations are the same in each of the three plots. The 8 K intercept should be placed at 85% of the distance from 300 K to 2 K, and the 50 K intercept should be placed at approximately 45% of the distance.

5.0 Conclusions

A finite difference model was created to calculate the conduction heat loads to the 2 K, 8 K, and 50 K temperature levels of a conductively cooled SNS fundamental power coupler used in the 8 GeV linac under design study at Fermilab. The RF losses under the 8 GeV linac operating conditions were included in the model. Plots were generated to show the calculated heat loads as functions of the intercept placements. There is an optimum placement of the 8 K and 50 K intercepts to minimize the Carnot power of the refrigerator cycle.

A gray surface enclosure radiation heat transfer model was also developed to estimate the radiation heat load from the power coupler to 2 K. The calculated radiation heat load is in good agreement with that calculated for the SNS project.

Efforts should be made to reduce the radiation heat load to 2 K. One possible method is to reduce the emissivity of the inner conductor, either by using a highly polished copper surface or by plating the copper conductor with a low emissivity metal such as silver or gold. A second possible method is to use a baffle to reduce the view factors into the 2 K beam pipe.

References

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